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THE DISTRIBUTION AND REGIONAL CORRELATION OF DEVONIAN OIL SHALES IN THE EASTERN UNITED STATES

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RESOURCE STUDIES

The Devonian-Mississippian black shales of the Eastern United States contain varying amounts of organic carbon that can range up to nearly 25 percent by weight or as much as 40 percent by volume (1) and when they are retorted they will yield shale oil. The Fischer Assay yield is typically less than 10 gallons of oil per ton of rock. Such a yield by conventional retorting methods has been low enough when compared to Western oil shales to have limited interest in Eastern shale until new retorting technology enabled the Eastern shales to assume a competitive position. Eastern oil shales having levels of organic carbon similar to those of Western shales react comparably when a hydrogen retorting method is used (Table I).

TABLE I

U. S. OIL SHALES

	Eastern	Western
Ultimate Analysis, (dry basis) wt%		
Organic Carbon	13.7	13.6
Hydrogen	1.6	2.1
Sulfur	4.7	0.5
Carbon Dioxide	0.5	15.9
Ash	78.3	66.8
Fischer Assay Analysis		
Oil Yield, wt%	4.6	11.4
Assay, gal/ton	10.3	29.8
HYTORT Yields		
Oil Yield, wt%	9.1	--
Assay, gal/ton	23.2	--

The Eastern shales occur over a wide expanse from New York to Oklahoma and from Iowa to Alabama as shown on Provo's 1971 map (2), (Figure 1), yet as rocks that must be mined to be retorted, the shales of greatest potential are those near, or at the surface. A study of the Devonian-Mississippian Shales by the Institute of Gas Technology (IGT) to test them as feedstocks for the HYTORT ® process (3) included an intensive sampling of the shales. IGT has sampled more than 180 locations from 15 Eastern and Western states and has taken more than 600 shale samples for analysis. Included in these were large-tonnage samples (10 to 50 tons) of shale from seven Eastern shales and from four Western geologic basins to provide the quantity necessary for a process development unit (PDU) having a 1 ton/h shale capacity which has been operating in Chicago since 1976 (4). Four criteria for resource assessment were imposed by IGT (5) in calculating resource estimates:

- Organic carbon at least 10 percent by weight
- Shale at least 10 feet thick
- Stripping ratio less than 2.5 to 1, and
- Maximum overburden thickness less than 200 feet.

The results of the sampling and testing program suggest a resource base in excess of 420 billion barrels of shale oil (Table II) from shale near the surface. The map (Figure 2) shows the area in square miles considered accessible in each of the several states studied, along with thickness and richness data. The most important areas are in the States of Kentucky, Tennessee, Indiana, and Ohio, where nearly flat-lying beds, averaging 30 to 40 feet thick, are exposed at the surface in an outcrop belt nearly a thousand miles long.

TABLE II

ESTIMATED RESOURCES OF SHALE OIL RECOVERABLE BY THE HYTORT PROCESS IN THE APPALACHIAN, ILLINOIS, AND MICHIGAN BASIN AREAS

State	Total Area Suitable for Surface Mining, sq. mi.	Resources Recoverable by Aboveground Hydroretorting	
		billion bbl	bbl/acre
Ohio	980	140	222,000
Kentucky	2650	190	112,000
Tennessee	1540	44	44,000
Indiana	600	40	104,000
Michigan	160	5	49,000
Alabama	300	4	21,000
Total	6230	423	

The shales have been studied for many years by many people and for many reasons. They are the source of a natural shale gas, a resource that has seen the development of over 9000 gas wells and is the subject of active research interest today (6). The shales are potential ores for uranium, some as high as 0.033 percent of that metal (7), and they are relatively high in other metals (8). They are likely source rocks for conventional crude oil and natural gas where they have been buried deeply enough to have matured. The variety and widespread nature of the black shales has led to a complex local nomenclature (Figure 3). The units named have been identified and used by stratigraphers because they are mappable, visibly recognizable in outcrop or from drill-hole data, and not because of any uniform geochemical characteristics. The stratigraphic framework based on color and natural radiation level that was available when Eastern shales became of recent interest proved inadequate to the understanding and prediction of retorting behavior and resource grade. The vertical and lateral variations within the rocks (9) were found to be great enough to require more detailed testing and correlation of shales from state to state as well as from basin to basin.

The manner of deposition of the black shales is still a subject of academic argument; it is complicated by the fact that organic matter in marine sediments can be preserved in a number of depositional environments, which share a common and necessary requirement of little or no oxygen (10).

One problem in developing a regional shale stratigraphy is the lack of fossils in the shale that can serve as time markers. A notable exception (Figure 4) is the fossil alga Foerstia, widely scattered across the Appalachian Basin but only found in a very narrow vertical range. Foerstia lived for a brief span of geological time and thus serves as a "time line" wherever found. As astronomical observations can be used to give precision and correlation to ancient history, so a fossil like Foerstia provides an accurate correlation of geologic events. The recent discovery by Kepferle (11) of the fossil alga in the Illinois Basin has changed the age relationship of rocks between that basin and the Appalachian Basin.

STRATIGRAPHIC INTERPRETATIONS

The Devonian rocks do not present as complete a record as many of the older, more deeply buried rocks, because there has been a loss by erosion of unknown thicknesses of Devonian section over the positive areas that separate the geologic basins. These positive areas, or arches, developed and were active at various times during the geologic past (Figure 5). The Algonquin Arch in southwestern Ontario existed as an early Upper Cambrian and Lower Ordovician feature (12), but was not sufficiently active during Late Devonian to prevent a continuous deposition of the Antrim/Kettle Point/Ohio Shales across Ontario. The Findlay Arch now separating northern Ohio from southeastern Michigan did not come into existence until after Devonian time (13) and thus would present no impediment to a complete deposition of black shales from Michigan through northwestern Ohio. These assumed rocks were lost by erosion as the arch lifted following the Pennsylvanian Age. Likewise, the Kankakee Arch now separating the modern Michigan and Illinois Basins in northwestern Indiana did not develop until after the Pennsylvanian and could not have been an obstacle to continuous black shale deposition of Antrim/New Albany from Michigan to Illinois; however, these shales no longer exist. The effect of the older Wisconsin-Illinois Arch on the deposition and survival of the Late Devonian shales can be seen in the composited Devonian shale map (Figure 6). In east central Illinois, the shale thins to less than 100 feet over the arch, and the map trace of the outcrop is displaced to the south.

The inference that continuous and related deposition of shales did occur can be supported by the evidence of surviving lithofacies patterns and unit thicknesses. It is axiomatic that space must be available if sediments are to accumulate; thus, the preserved thickness of a sedimentary unit is one measure of the crustal subsidence. Downwarped "negative" areas will receive measurable thicknesses; however, when there is erosion of rock caused by crustal uplift in "positive" areas, the volume and thickness of rock lost cannot be determined easily. Where rocks are eroded, a gap in time occurs. Richter-Bernberg (14) holds a general principle that by far the greatest part of geologic time is unrepresented by remaining sediments; this would seem to be the case with Devonian Shales. The black shales of central Kentucky and Tennessee that are deposited (and preserved) over the positive areas southward of the Cincinnati Arch measure only a few tens of feet thick or may be absent. These few feet of shale resting on Silurian or older rock and overlain by Mississippian or younger rock are all that exists in that area to represent 50 million years of the Devonian; whereas, in the Appalachian Basin, more than 11,000 feet of Devonian sediments accumulated.

The thickness of Devonian Shale (15) (Figure 6) in northwestern Michigan establishes a depocenter some distance northwest of the center of the modern structural Michigan Basin. A similar area in west central Illinois received an unknown volume of Devonian sediments and has been called the Western Depocenter by Illinois stratigraphers (16). These two depocenters may have been related and joined as one across the line of the older Wisconsin-Illinois Arch. The Ellsworth equivalents in Illinois are not preserved in their original thickness, because they were eroded by uplift before being covered by the Burlington Limestone of Mississippian age (16). These shales thicken from about 100 feet to 160 feet in about 15 miles (4 feet/mile) as they approach the depocenter from the southeast, but the increase in thickness beyond 160 feet, whatever that may have been, was removed by erosional truncation. The Ellsworth of Michigan reached a thickness of about 800 feet (17) and probably was not eroded.

A striking feature of the upper Antrim in Michigan is the abrupt change in rock type from black, organic-rich shales in the east to greenish-gray, organic-poor shales in the west. These different shales were deposited contemporaneously and exist in a facies relationship to each other. The zone of lithofacies change is shown on Fisher's (17) map of the green-gray Ellsworth Shale, and a similar facies change has been noted in Indiana (18). The zero line from Hasenmueller's (19) Indiana Ellsworth map has been combined (Figure 7) into a regional composite with Fisher's as evidence of a single depositional control with a northwestern source for sediment and an environment of deposition unfavorable for the preservation of organics throughout a wide area of western Michigan and northern Illinois. A common feature of the Ellsworth/Antrim in Michigan and the Ellsworth/upper New Albany in the Illinois Basin is a similar overall shape. The configuration in cross section can be illustrated by a schematic drawing (Figure 8) depicting two episodes of deposition. The first (A) called the "lower black" shale here is widespread, carries a consistent internal gamma ray signature, and is relatively uniform in thickness. The second, composed of two facies, is widespread and is most apparent as a wedge of sediment having a black, organic-rich facies (B) that forms the thin side of the wedge and a green-gray, organic-poor shale (C) that forms the thick part of the wedge. The black shale (B) is here called the "upper black" shale, and the gray shales (C) are here called the "green-gray facies".

Applied to the Michigan Basin in east-west cross section, the "lower black" shale, (A) represents the Antrim of western Michigan and that part of the eastern Antrim identified by Subunits 1A, 1B, 1C, and 2. The "green-gray" facies (C) is the Ellsworth Shale, and the "upper black" is represented by all Antrim above Unit 2 and below the base of the Bedford Shale. The uniformity of the lower beds of the Antrim has been noted by several others (17, 20), and a westward source for the Ellsworth has been postulated by several (17, 20-22). Nevertheless, the westward source seems more applicable to those beds above the western Antrim, i.e., above the beds termed "lower black" in this paper.

The schematic black shale sequence (Figure 8) also can be applied to the upper New Albany of the Illinois Basin, where a facies relationship of the green-gray Hannibal/Saverton Shales with the Grassy Creek has been described by Lineback (23).

> "The upper part of the Grassy Creek and its Indiana equivalents (the combined Morgan Trail, Camp Run, and Clegg Creek Members) grades laterally northwestward into a thickening wedge of greenish-gray shales and siltstone, the Saverton and Hannibal Shales in Illinois, the Ellsworth Member in Indiana."

Thus, the Hannibal/Saverton (C) and the upper part of the Grassy Creek (B) form the wedge in the sequence. The "upper black" can be postulated to be that part of the Clegg Creek Member of the New Albany in Indiana above the newly discovered Foerstia zone (11). If the lithologic and gamma ray correlations developed by the Illinois Geological Survey stratigraphers are correct (16), the Foerstia zone would appear to cut the Grassy Creek of Illinois into "upper black" and "lower black". If Foerstia extends into northwestern Illinois, it should be found just below the base of the Saverton in the top of the western Grassy Creek.

The sediment source for this great wedge would have been from the northwest, but the sediments below the presumed position of Foerstia in the Illinois Basin are not necessarily from that same source. Kepferle's discovery of Foerstia on the eastern side of the Illinois Basin has established that the great bulk of black shale in Illinois predates much of the black shale in eastern Kentucky and Ohio (24).

The hypothetical black shale sequence is also applicable to various parts of the Sunbury Shale (Mississippian) in Michigan and Ohio. In eastern Michigan, the Sunbury increases from a typical thickness of 20 to 40 feet across most of the basin to over 140 feet in Sanilac County, where both cores and gamma ray logs document a local increase in thickness, that is shown on Fisher's 1980 isopach map of the Sunbury. The "normal" Michigan Sunbury represents the "lower black" (A); the unusual added thickness in the east becomes the "upper black" (B) with some part of the lower Coldwater Shale assumed to be a facies equivalent and representing part (C) of the upper wedge. The question of whether such a facies relationship exists between a part of the Sunbury and the Coldwater has not been answered, and to date no evidence can be advanced to support a division within the lower Coldwater Shale of central Michigan. Unfortunately, the Coldwater Shale, over 800 feet thick, is a unit of no economic interest and has drawn little investigation.

A similar geometry exists in the Sunbury of Ohio and can be illustrated on a section from the 1954 publication (25) by Pepper et al. (Figure 9). An abrupt increase in thickness of dark shales, logged as Sunbury by drillers, lies over a "normal" widespread Sunbury over most of Ohio. The widespread unit represents the "lower black" (A), the abnormal thickness of dark shale becomes the "upper black" (B), and the organic-poor facies (C) is represented by a part of the Orangeville Shale at the base of the Cuyahoga Group. The demonstration of a facies relationship and a division within the lower Cuyahoga is not available at this time; thus, as in Michigan, a two-part Sunbury based on shape must be considered as conjecture.

That two genetic types of Sunbury exist in the Appalachian Basin has been recognized by Van Beuren (26), who attempted to explain the geometric relationships between black shales and laterally adjacent gray/green shales and siltstones by means of a cycle of transgression and regression. His transgressive unit is "characteristically thin and widespread", and his regressive black shale is thicker, more laterally restricted and represents the distal facies of laterally adjacent non-black clastics. Related to the hypothetical black shale sequence (Figure 8), Van Beuren's transgressive unit is the "lower black" (A), the regressive Sunbury unit is the "upper black" (B), and the clastics represent the green-gray facies (C). The shape of the wedge of "upper black" (B) and its green-gray facies (C) requires that clastics came from the direction of the thick end and that the "upper black" was a deeper water deposit formed a greater distance from the source. The upper wedges are relatively local as compared with the "lower black" units, which are regional; the Lower Antrim/Kettle Point/Ohio (in part) is continuous and is representative of the black shales to be deposited over the arches between the three basins. The source of the lower unit is not as apparent as for the upper unit (B/C). If the "lower black" is cyclic as Van Beuren advocated for the lower Sunbury, it should have a source similar to the overlying wedge.

A westward or northwestward source for Ellsworth/Upper Antrim and for Hannibal-Saverton/upper Grassy Creek is appropriate for the overall geometry of an "upper shale" body. It is clear that great volumes of clastic material in the Appalachian Basin came from the east and that some of the black shale sequence also applies east of the Cincinnati Arch (in mirror image), I believe that some of the black shales in the basin will prove to be more regional in nature and of the "lower shale" type (A).

The pulses of increased clastic influx reflect tectonic activity, as has been suggested by Ettensohn and Barron (27, 28), but with the addition of a northwestern landmass to provide material west of the general line of the Algonquin and Cincinnati Arches. These pulses are represented by the upper wedges (C/B). Between pulses, there is widespread deposition of the "lower black" type of shales which, for the lower Antrim and Sunbury equivalents, were little influenced by arches. The southwestern source suggested by Ettensohn and Barron (27) seems very plausible for the lower shales (A) of the Illinois and Appalachian Basin and of Michigan as well.

The 50 million years of the Devonian Age is sufficient for tectonic control of a series of local wedges alternated with periods of truly regional deposition, with each episode spaced apart by great periods of little or no deposition (unconformities) within the Devonian-Mississippian Shales of the Eastern United States.

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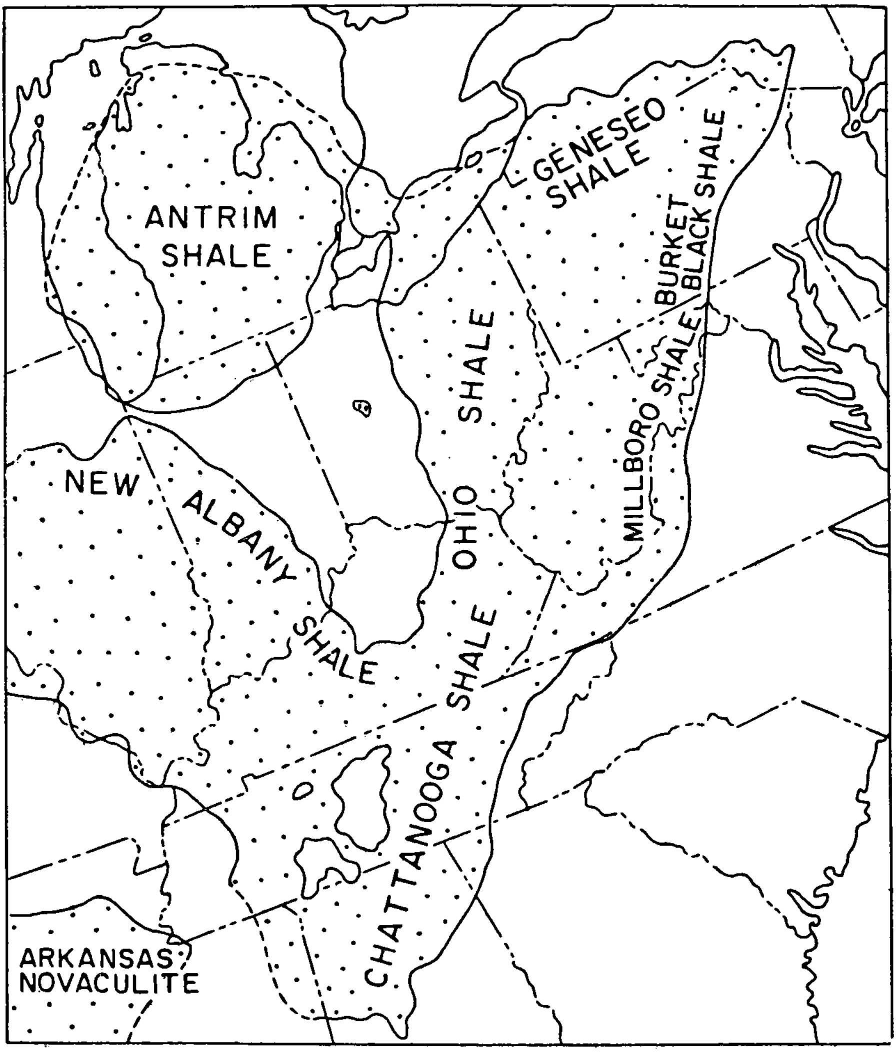

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Figure 1. Principal Devonian Oil Shale Deposits of the Eastern United States

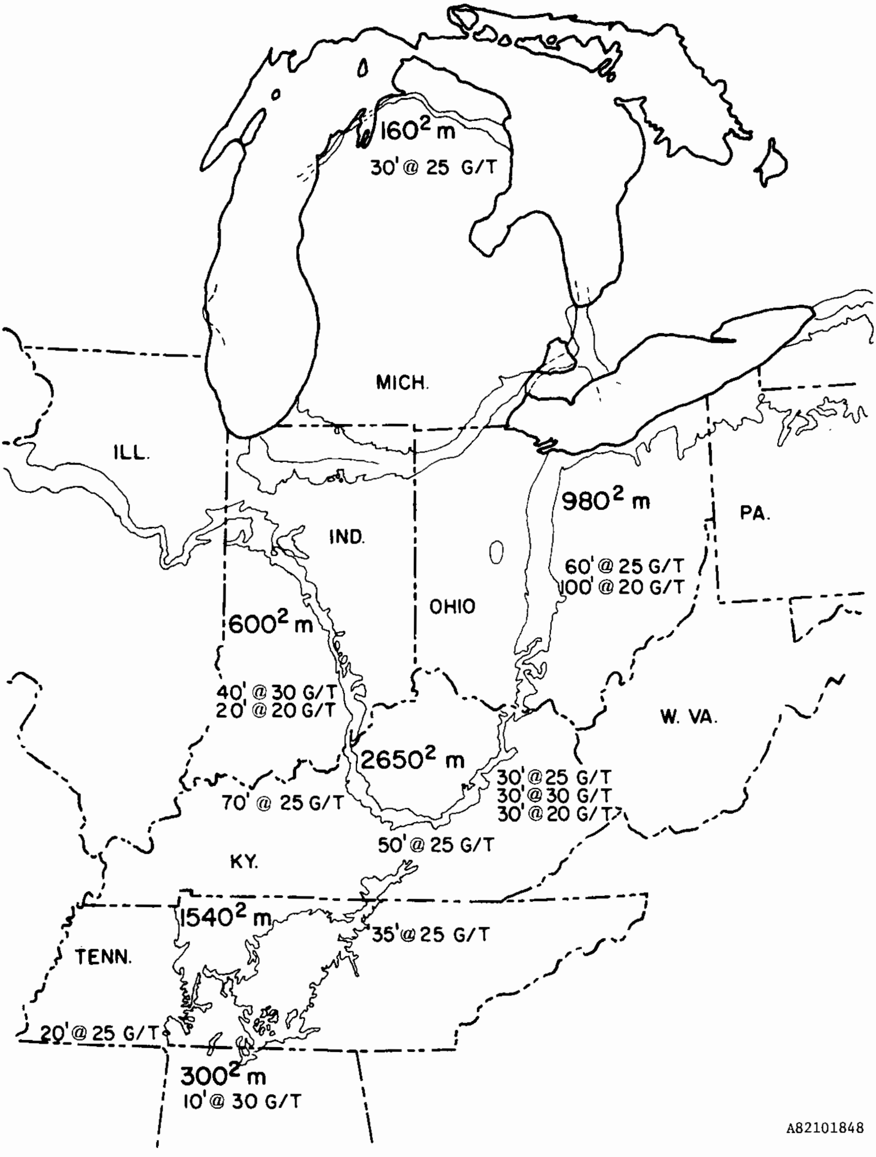

Figure 2. Map Showing Outcrop Areas and Resource Data for the Devonian-Mississippian Oil Shales of the Eastern United States

Outcrop is shown by line where narrow.

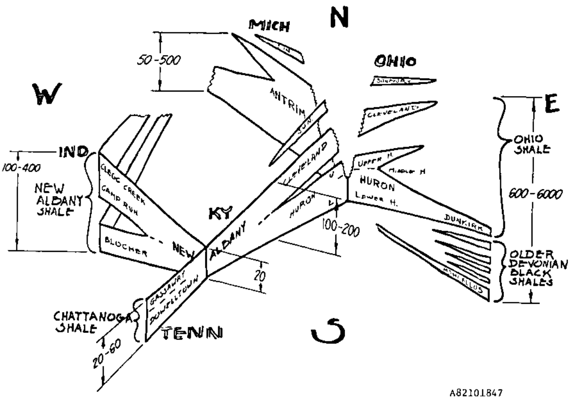

Figure 3. Fence Diagram Showing Black Shale Nomenclature and Thickness in Feet

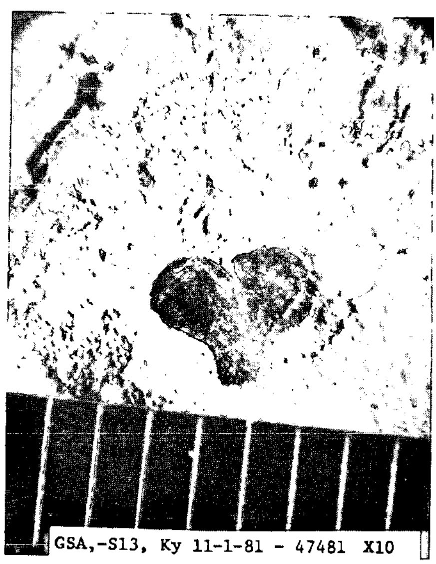

Figure 4. Photomicrograph of Foerstia From the Huron Member of the Ohio Shale Near Vanceburg, Kentucky (Millimeter Scale in Figure.)

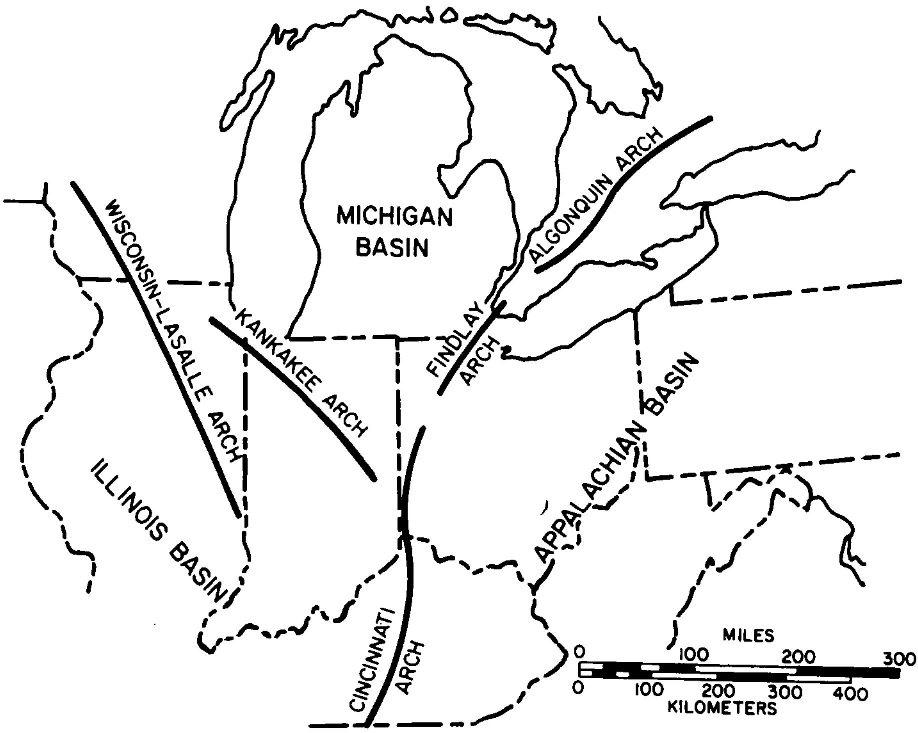

Figure 5. Major Structural Features Mentioned in the Text

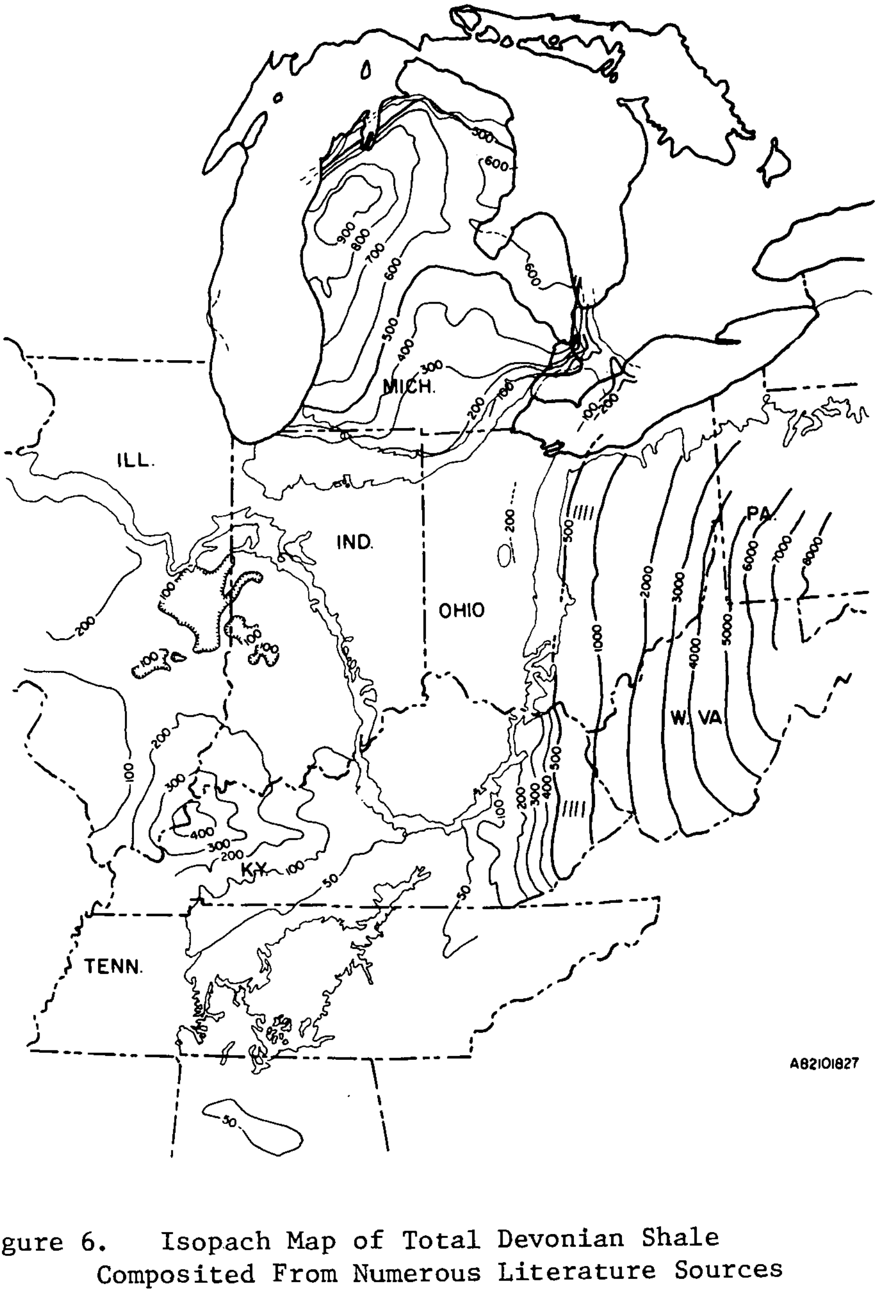

Figure 6. Isopach Map of Total Devonian Shale Composited From Numerous Literature Sources

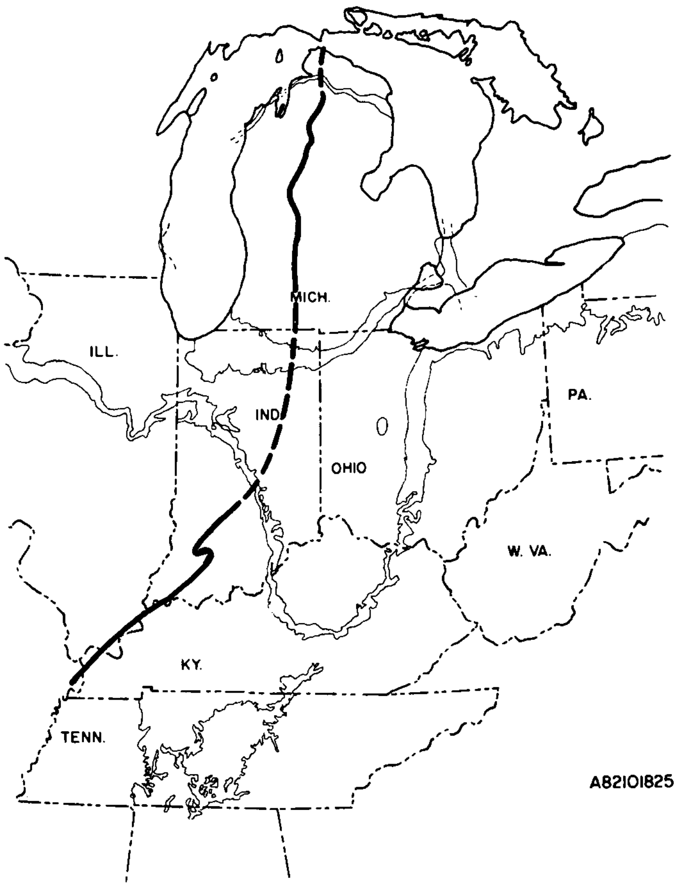

Figure 7. Regional Map of the Ellsworth Shale Zero Line, Green-Gray Ellsworth-Type Shales to the West and Black Antrim-Type Shales to the East

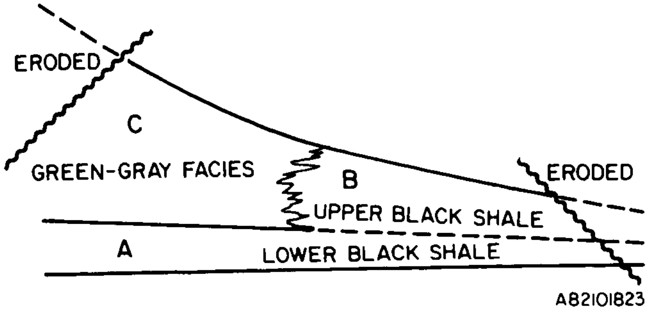

Figure 8. Hypothetical Black Shale Sequence

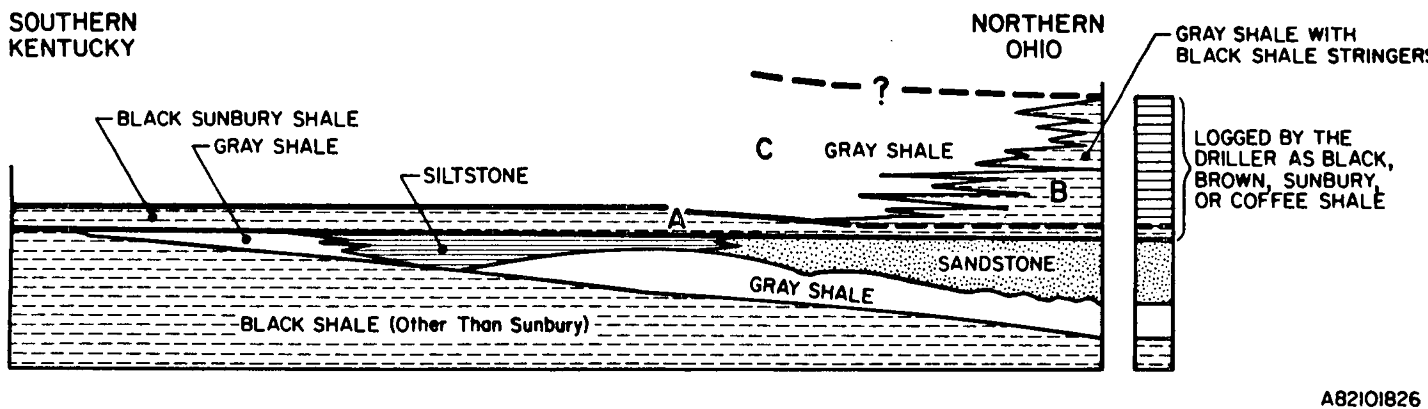

Figure 9. Generalized Cross Section From Southern Kentucky to Northern Ohio Showing the Abnormal Thickness of Sunbury Shale as Recorded by Drillers — After Pepper (25)

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